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Introduction.

Although electrical closing switches have been used reliably for many years in the studies of high explosives (HE) and in explosive-driven shock wave experiments, we have chosen to replace electrical switches with fiber optics in much of our nuclear weapons work and related physics experiments for several reasons. Foremost is safety, the ability to place the "pin" in direct contact with the HE without fear that energy will get into the HE and detonate it. Other issues include improved timing and the capability of determining the amplitude of the signal to help in discriminating against shock waves that might close an electrical switch.

Another useful diagnostic is a color temperature measurement consisting of several optical fibers stood off from the detonating HE but aimed so as to detect light from the detonation. The fibers can have collimating lenses if they are far from the explosion, and each detector has a narrow-band optical filter of a different wavelength.

We are beginning development of other optical diagnostics, including a pulsed laser diagnostic, which measures the amount of fluff or spall leaving the surface of a material shocked by an explosive, holography to look at the sizes of the emitted particles, and an optical interferometer to measure the position of the front of the moving, shocked surface.

Fiber Optic Pins.

Our initial motivation in fielding fiber optic pins grew out of a desire to eliminate the wires entering the canister lid on an underground nuclear test for safety reasons. We found that by using fibers we could safely place them in contact with the HE, or even embed them in a hole machined into the explosive, without fear that energy might get into the HE and detonate it. As a result we get much better timing results than with electrical shorting pins, which must be fastened to the outside of the nuclear explosive radiation case. The delay in transit time through the case increases the uncertainty in the electrical pin timing measurements by an order of magnitude. The high-resolution fiber optic data also give us an accurate measure of the HE detonation velocity, which has been very useful in calculations of the one-point-detonation safety of nuclear explosives.

A fiber optic "closure pin" consists of a bare fiber with its end coated with a thin metal layer, normally aluminum or chromium, just thick enough to keep out light. When the detonation wave strikes the tip of the fiber, it lights up and sends a signal to a detector at the other end. Successful operation requires two components, sensitivity calibration and careful timing. Calibration involves knowing the fiber core size and numerical aperture, the losses in the connections, and the detector efficiency, so that it is possible to estimate the signal size. Then we can identify the correct signal in the presence of noise or shock waves that may be present. Timing consists of measuring the optical transit time delays of the fibers and detectors to get precise relative times for the signals, especially important when measuring the shape or velocity of a detonation front.

We use streak cameras to record the pins if there is a large number of them or if we need very high time resolution. More typically the detectors are either photomultipliers or avalanche photodiodes with amplifiers to increase the sensitivities. Bandwidths range from below 100 MHz to about 500 MHz, and the threshold for signal detection is about 1 µW of light. When less bandwidth is needed, we filter the electrical output to reduce the noise. DC coupling of the detector and amplifier are very useful during set-up but are difficult to achieve for bandwidths above 200 MHz. For applications where the expected signal amplitude is very uncertain and relatively immaterial, we use non-linear amplification to compress the signal output, so that the recorded signal has a larger dynamic range. Signals are recorded on digitizers with sampling rates from 100 to 2000 Msample/s. Figure 1 shows data from a pin made of a 100-µm-diam-core fiber in contact with HE. An optical receiver with a compressed-gain amplifier detected the light, and a 100 Msample/s digitizer recorded it.

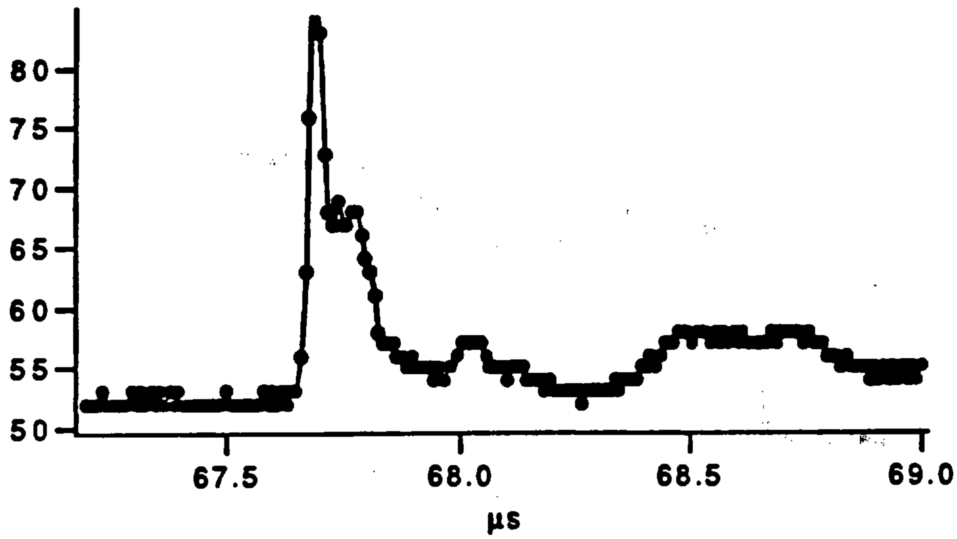

Figure 1. Data from an optical pin in contact with detonating high explosive. The vertical scale is roughly exponential with a peak value of a few hundred microwatts and a noise level of about 0.1 µW.

The same general type of fiber optic pin, a bare fiber and an optical detector, is also useful in detecting moving material as well as shock waves. For example, we use fiber optics to detect a flyer plate in an HE-driven shock wave experiment if sufficient energy can be deposited into the fiber to heat it and generate a detectable signal. We can detect strong shocks, in some cases down to 100 kbar or less in pressure.

Figure 2 shows data from 100-µm-diam fiber optic pins embedded in a 2-mm-thick aluminum plate. The upper curve shows a pin that was flush with the front of the stationary plate, where contact occurs, and the lower one is for a pin that protruded 1 mm beyond the plate. An aluminum flyer plate < 1mm thick struck the pins at 3 mm/µs. An increase in the lower signal about 300 ns after the initial contact indicates the time when the flyer plate struck the stationary aluminum plate at the base of the protruding pin. The resulting shock transmits more energy into the glass than the contact of the flyer with the pin tip, and hence there is an increase in the black body temperature of the fiber. Note that we believe that the heated fiber is opaque behind the shock front. Thus the signal depends only on the temperature right at the shock front, not behind it.

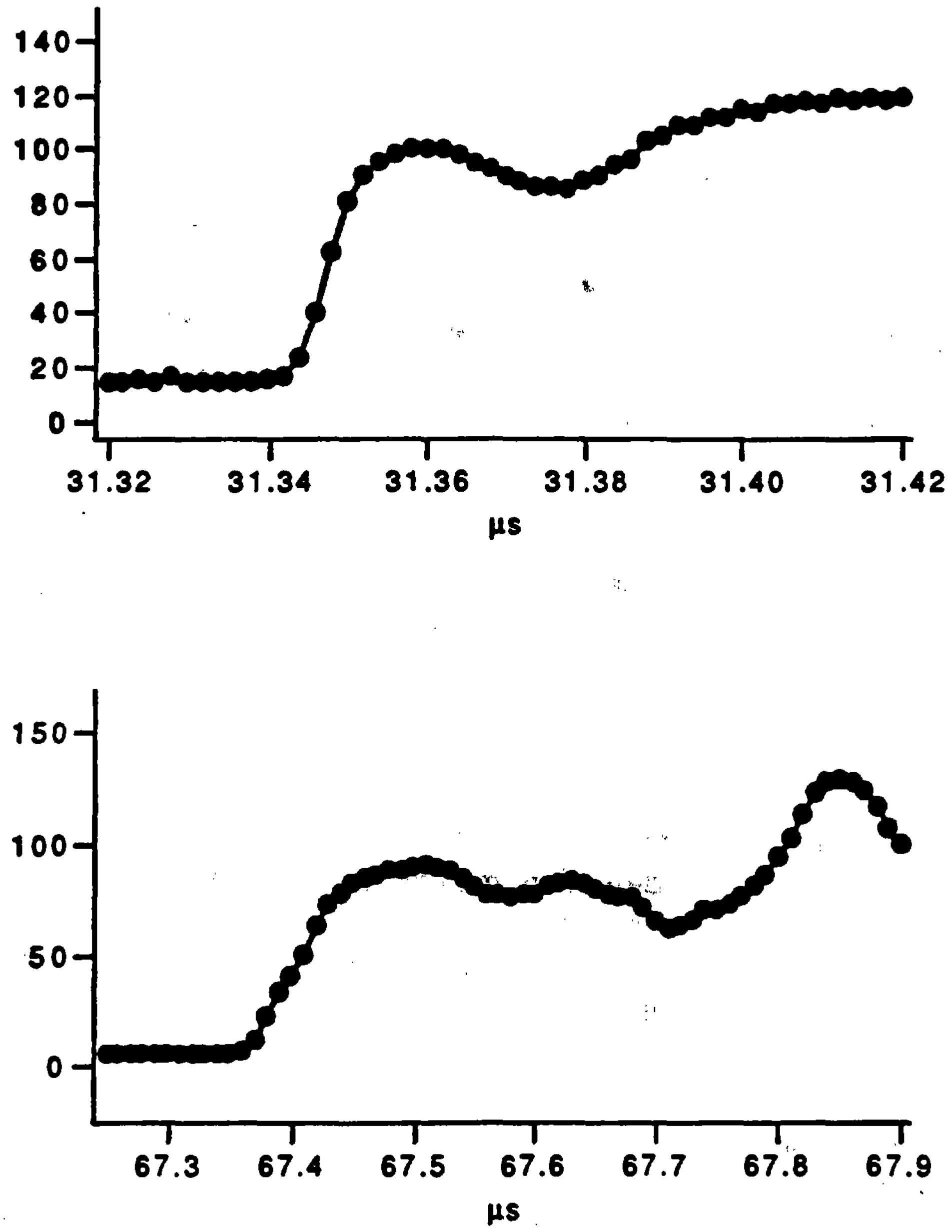

Figure 2. Data from fiber optic pins in a stationary aluminum plate detecting an aluminum flyer plate moving at 3 km/s. The upper graph shows a pin that had its tip flush with the impact surface of the holder and was recorded by a 500 Msample/s digitizer. The pin represented in the lower graph protruded 1 mm beyond the impact surface. Its tip was struck at 67.4 µs, and just after 67.7 µs the flyer struck the stationary pin holder and generated a signal increase. Signal rises are slower than in the top graph because of a greatly-reduced system recording bandwidth.

An important aspect of a successful fiber optic pin experiment is a good estimate of the light signal to be obtained. The signal is calculated from Planck's black body formula, making corrections for 1) the solid angle that the source subtends at the fiber; 2) the numerical aperture of the fiber, which determines the angle an accepted light ray can make relative to the fiber axis; 3) the fiber core diameter; and 4) the optical bandwidth of the system, including the optical filter and the detector.[1] The key to getting the black body emission right is a good temperature estimate. For fused silica quartz, which comprises most of the fibers we use, the temperature has been measured as a function of shock pressure up to about a megabar.[2] For a shock travelling obliquely to the fiber axis, the pressure in a quartz fiber can be calculated by assuming an impedance match from the shocked material into the quartz.[1] When the shock direction is along the fiber axis, the quartz pressure is usually higher because the shock reflects internally in the fiber. We have found that the best way to estimate the internal quartz pressure for an axial shock is to assume that the shock velocity in the fiber is the same as in the shocked material surrounding the fiber.[3] That is, assume that a steady state exists because the fiber diameter is small enough that the shock front is carried along in a fixed position relative to the main shock. This condition requires that no shock energy be allowed to jet ahead around the fiber, and that requires a good seal around the fiber. (We usually make the fiber hole as small as possible and use epoxy, perhaps thinned with acetone, to fill the hole around the fiber.)

Figure 3 shows a calculated fiber optic signal for fibers in aluminum as a function of the aluminum shock pressure. In one case the shock is oblique to the fiber axis, and in the other the shock is axial. Our threshold for detection is a little below a microwatt of light, so the aluminum pressure thresholds for these two cases are around 600 kbar and below 100 kbar, respectively. Measurements at several aluminum pressures have generally confirmed these calculations.

We use an optical filter, either narrow band or broad band, to define the detected wavelength and its width. Typically, we detect light around 850 nm. For this wavelength, the optical emission changes very rapidly with temperature below a megabar quartz pressure. Thus a measured optical signal can be rather crude and still give a pretty good temperature (and hence also pressure) measurement. This pressure estimate is very often useful in assuring that the signal we saw was indeed caused by the shock

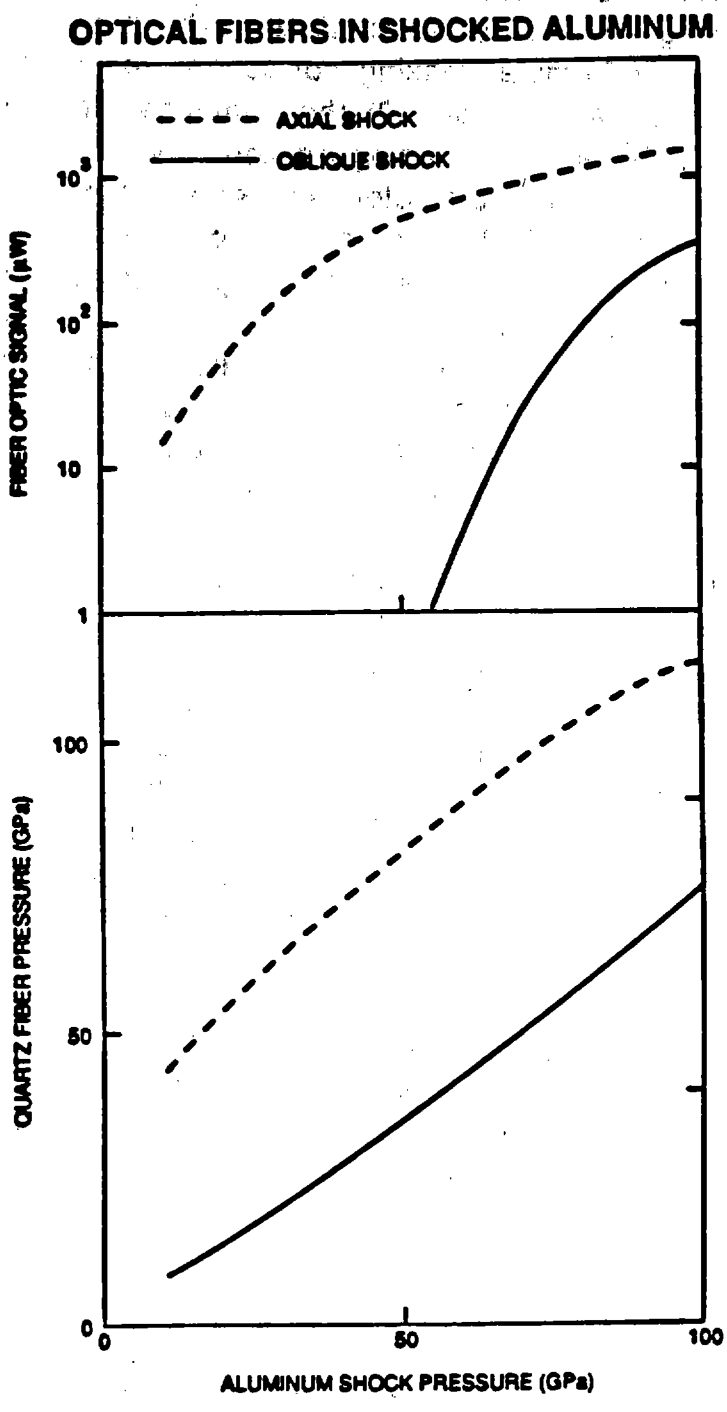

Figure 3. Calculated signals for 100-μm-diam-core optical fibers in shocked aluminum. A bandwidth of 300 nm around a central wavelength of 850 nm is assumed. When the shock runs along the fiber axis, the shock pressure is higher and more light is produced than for a shock oblique to the axis.

we intended to measure. Many times there have been more than one shock wave signal in an experiment, and a good signal estimate has meant the difference between success and failure of the experiment.

For high-accuracy shock experiments, such as equation-of-state work, it is necessary to time the relative delays in the fibers carefully. We can do this to a precision of better than 1 ns over fiber lengths of hundreds of meters either with an optical time-domain-reflectometer (OTDR) or by injecting laser light simultaneously into many fibers and measuring the delays directly. We can also adjust the delays. For recording on a streak camera it can be important to have all the signals as simultaneous as possible so that the camera can be swept fast to get good time resolution. Figure 4 shows streak camera signals from a molybdenum sample shocked to about 60 Mbar. Although the sample was 15 mm thick and the emitted signals from different depths in the sample were spread out over half a microsecond or more, the individual signals were delayed with optical fibers to arrive at the camera within a few tens of nanoseconds.

Temperature Diagnostics.

A cleaved fiber pointing at the source can be used to measure the black body light from a detonating explosive to determine the brightness temperature. Several fibers are used, each with a narrow band optical filter in front of the detector, so that we get a measure of the relative amounts of light at several wavelengths, typically in the range from 700 nm to 1.3 µm. This measurement requires a careful calibration of the optical receiver sensitivity, the losses in the fibers and connectors, the solid angle of the source at the fiber (or the numerical aperture, NA, of the fiber if the source fills the NA), and the filter transmissions as a function of wavelength. If needed for more light collection or to aim the fiber in a given direction, we use a graded-index lens on the end of the fiber. In principle we could do the measurement with just a single fiber and receiver, but we prefer to have two or three to provide redundancy and so that we can use their ratios to remove the need to rely on absolute calibrations. Black body temperatures above about 1800 K emit enough light in these wavelengths to be detectable with time resolution of the order of 10 ns.

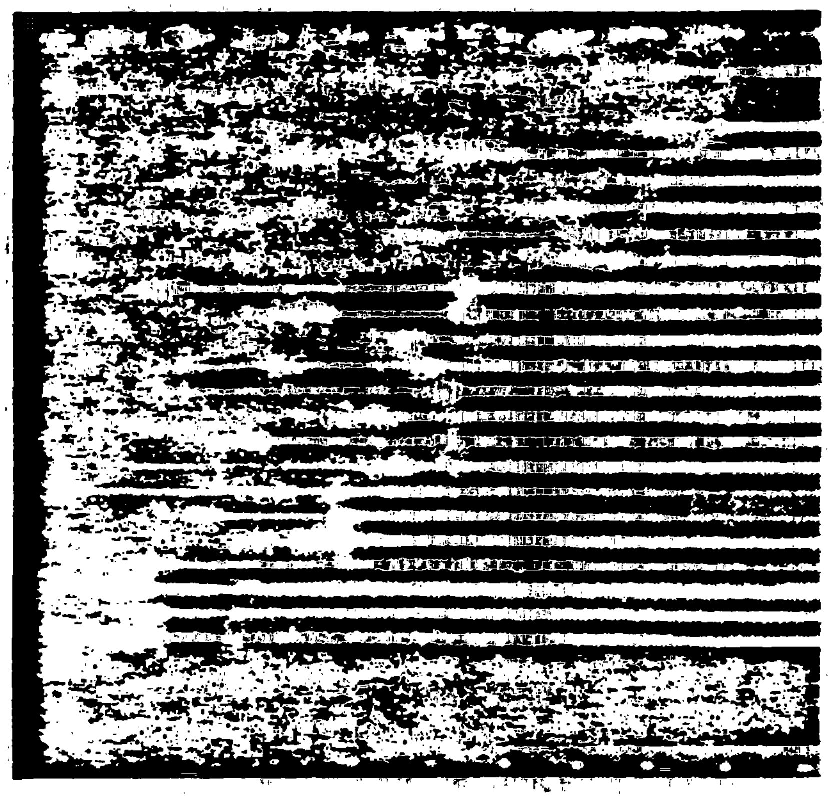

Figure 4. Shock wave data from a streak camera record of fiber optic pins in contact with a 15-mm-thick molybdenum sample struck by a shock of about 60 Mbar. Three pins were placed at the base of the sample and four pins were placed at each of five levels, every 3 mm in thickness. (One pin didn't work.) Although the shock reached the various levels over a time spread of about 500 ns, we delayed them so that they would all get to the streak camera roughly simultaneously so that we could speed up the sweep. The rows of dots are from a 10-ns-interval timer. The pins were not darkened at the tips, and as a result, some of the signals have prepulses from light that got around the sample. The prepulses can be removed to obtain correct data.

We have assembled equipment to detect IR light in the 1.5 to 4 μm region for a measurement of the temperature of a shocked surface around 1000 K. At this temperature there is very little visible emission, but the IR light should be adequate for a time-resolved temperature determination. Fluorozirconate IR-transmitting fiber optics carry the light to three mercury-cadmium-teluride detectors. Zinc-selenide lenses are used. We have built a vacuum system to prevent arcing on the surface when the shock breaks out. If we are successful, we will upgrade the detectors to indium phosphide.

Measurements of Small Particles

We are just beginning to test a diagnostic to measure the optical density of particulate matter ejected from a shocked surface. The tests involve backscattering light from a pulsed laser into a fast streak camera to determine the amount of particulate matter in the path. The method is similar to the pulsed LIDAR technology often used to investigate particulate matter in the atmosphere. We are starting with a 4-ps-long laser pulse and a 2-ps-resolution streak camera, giving a spatial resolution of about 2 mm. As soon as possible we will upgrade both the laser and the camera to optimize the resolution.

The first measurements with this technique were made on a vial filled with copper particles a few microns in size suspended in alcohol. As the copper settled to the bottom of the vial, the transmission increased and we saw the absorption coefficient change appropriately. Figure 5 shows the back scattering as a function of position in the sample, first with the copper settled out of solution, and then at later times after shaking the sample. We are now procuring round metal particles of a known size to better calibrate the scattering intensity and to learn whether forward scattering offers additional information about the particle sizes.

A related diagnostic, which does not involve fiber optics at present, is holography. Design parameters are just now being laid out For a system in which light can be passed straight through, such as a plane shock wave unloading into a vacuum, or the inside of a cylindrical shell shocked from the outside, we can use one-beam holography if the density of emitted particles is not too large. Our intention is to try one-beam holography on pulsed-current-driven, cylindrical metal implosions on the Los Alamos

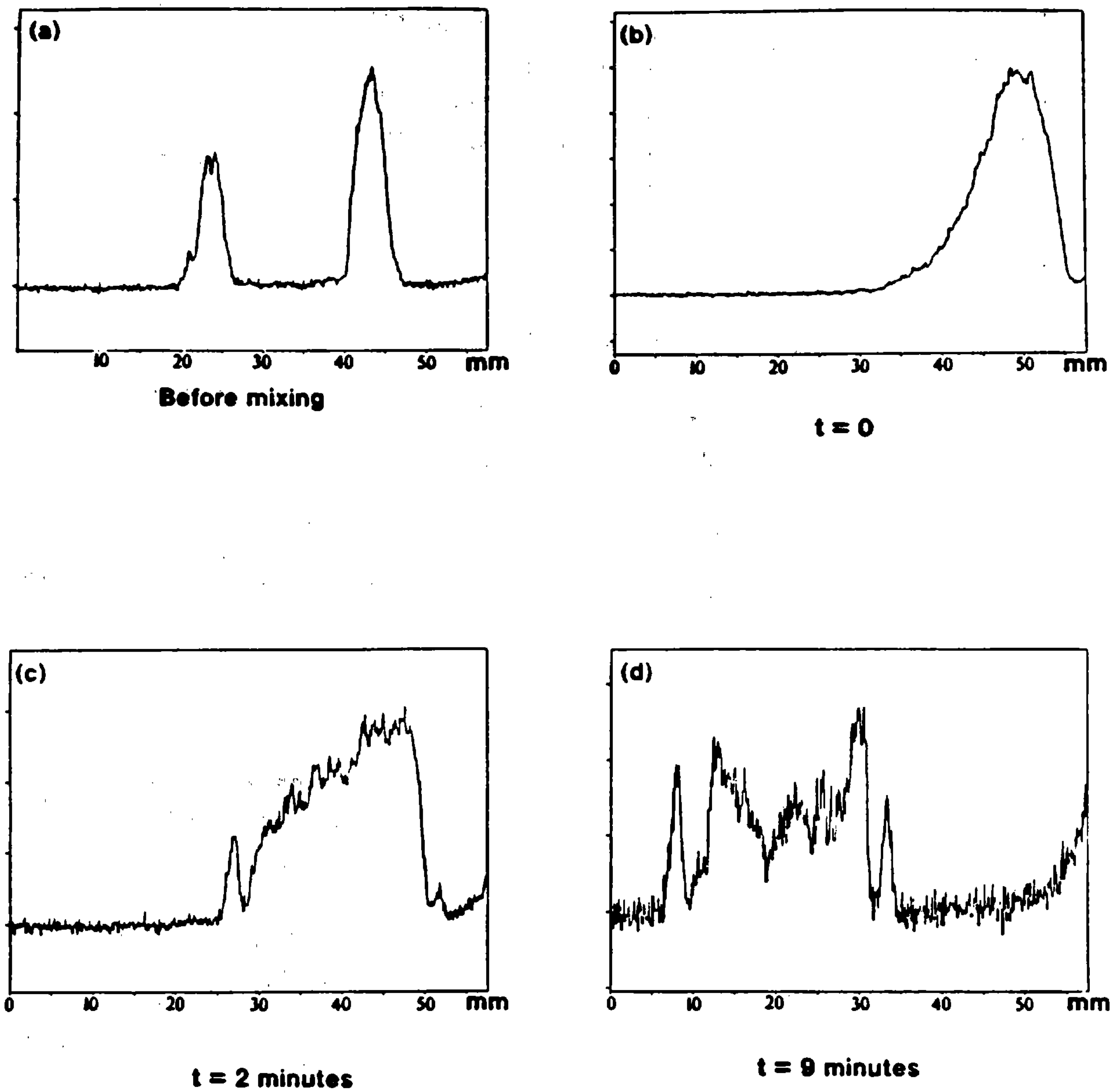

Figure 5. Streak camera data showing back scattering from a 4-ps-wide laser pulse striking a vial of 7-µm copper particles suspended in alcohol. The vertical scales show intensities, but the scales are different for each graph. The horizontal scales show thickness of material traversed. The narrow peaks before and after the main scattering data are from the glass windows. As time after mixing increases, the traces have progressively more of the copper settled out.

Pegasus capacitor bank. For more dense particle distributions and for systems where the light cannot be passed through, we will have to go to two-beam holography and reflection geometry. One interest we retain is in examining the inside of a spherical implosion with minimal intrusion into the spherical geometry. For this we will try two-beam holography.

Acknowledgments

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